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14. ABSTRACT

Gas-centered swirl-coaxial (GCSC) injectors have enjoyed much recent interest for use in LOX-hydrocarbon rocket engines in the US. (Prior to injection, the LOX is vaporized and combusted in a preburner and is introduced to the combustion chamber as gas.) Many GCSC injectors feature a dividing plate between the initial liquid fuel flow and the gaseous oxidizer flow. Generally this plate terminates with some thickness producing separated gas flow just prior to contact with the liquid. This recirculation zone and other flow factors cause the film and spray to be nonuniform in space and time. These nonuniformities are discussed in detail and suggestions are given for producing more uniform and predictable sprays. In addition to the influence of geometry, the impact of operating conditions is included in these studies.

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Film Behavior in Gas-Centered Swirl-Coaxial Injectors (Preprint)

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ABSTACT

Gas-centered swirl-coaxial (GCSC) injectors have enjoyed much recent interest for use in LOX-hydrocarbon rocket engines in the US. (Prior to injection, the LOX is vaporized and combusted in a preburner and is introduced to the combustion chamber as gas.) Many GCSC injectors feature a dividing plate between the initial liquid fuel flow and the gaseous oxidizer flow. Generally this plate terminates with some thickness producing separated gas flow just prior to contact with the liquid. This recirculation zone and other flow factors cause the film and spray to be nonuniform in space and time. These nonuniformities are discussed in detail and suggestions are given for producing more uniform and predictable sprays. In addition to the influence of geometry, the impact of operating conditions is included in these studies.

INTRODUCTION

The current focus on LOX-hydrocarbon rocket engines has fueled interest in a unique type of injector—a gas-centered swirl-coaxial (GCSC) injector[1,2]. The center gas flow is composed of GOX which has been combusted at high oxygen/hydrocarbon ratio in a preburner. While this injector type is used in Soviet rockets, it is relatively new in the United States. These injectors are unique because the atomization occurs within the injector body while the liquid is still bounded by a wall; in most injectors atomization occurs outside of the injector body when the liquid is in total contact with the gas[3,4]. As a result of the atomization location, GCSC injectors are particularly sensitive to their internal geometry and care must be taken in their design. Unfortunately, there have been limited studies of these injectors in the US and limited design criteria exist.

The main interests in any study of injectors for rocket applications are the predictability of droplet size and distribution. Preferable distributions are steady in both time and space. This work focuses on spray uniformity and how it relates to the geometry of the injector and the operating conditions. Spray nonuniformities can lead to a variety of undesirable behaviors in rocket engines. Some nonuniformities may couple with the combustion process producing combustion instabilities which can destroy an engine. Nonuniform distributions can lead to poor mixing which could cause nonuniform heat release; poor mixing degrades performance and may lead to localized overheating (or underheating in an expander-cycle engine).

The current work details the types of spray instabilities and nonuniformities observed during parametric testing of GCSC injectors. This testing also indicates that these undesirable behaviors are related to the injector geometry and operating conditions. Prior to presenting these results, a description of the basic geometry of GCSC injectors is given as part of the explanation of the experimental set-up.

EXPERIMENTAL SET-UP

A gas-centered swirl-coaxial injector relies on the energetic, fast-moving gas flow to produce droplets from the swirling, wall-bound film. The film is created by introducing the liquid, in this case water, through holes drilled tangential to the injector cup. The unswirled gas, here gaseous nitrogen, enters down the centerline. A schematic of the current injector is given in Fig. 1. This injector was designed to be modular. An acrylic outlet section, the only portion shown in the schematic, is changeable to give an outlet radius of 7.620, 9.525 or 11.43 mm (0.3, 0.375 or 0.45 inches). An acrylic insert forms the last portion of the gas post and the initial shelter for the liquid; it is also interchangeable to allow gas post radii from 3.429 mm to 9.271 mm (0.135 to 0.331 inches) and initial film thicknesses of 1.321, 1.651 and 1.981 mm (0.052, 0.065 and 0.078 inches). Upstream of the acrylic section is a stainless steel section which consists of ~180 mm of gas post with a fixed radius of 6.35 mm (0.25 inches). The specific injector geometries are given in Table 1. While the experiment was designed to take advantage of differing gas

velocities produced by changing the post radius, the change in geometries also produces a variation in the height of the lip initially separating the gas and liquid flows.

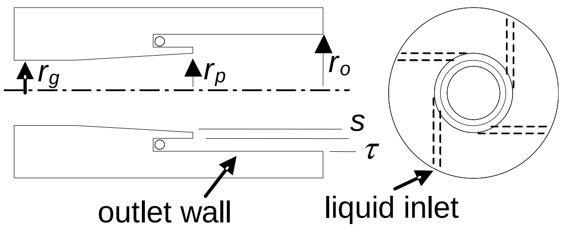

Figure 1: In this schematic of a gas-centered swirl-coaxial injector r_g represents the initial gas radius (always 6.35 mm), r_p the gas post radius at the end of the sheltering lip, r_o the outlet radius, s the step height and τ the gap height. Table 1 lists the values of these dimensions used in the experiments.

Name	r_o (mm)	τ (mm)	r_g (mm)	s (mm)
ODHUTD	7.620	1.321	3.429	2.870
ODPDTD	7.620	1.321	5.461	0.838
ODHNTN	7.620	1.651	4.445	1.524
ODPDTN	7.620	1.651	5.461	0.508
ODHUTU	7.620	1.981	3.429	2.210
ODHDTU	7.620	1.981	5.461	0.178
ONPDTD	9.525	1.321	5.461	2.743
ONHNTD	9.525	1.321	6.350	1.854
ONPDTN	9.525	1.651	5.461	2.413
ONPNTN	9.525	1.651	6.350	1.524
ONPUTN	9.525	1.651	7.468	0.406
ONPNTU	9.525	1.981	6.350	1.194
OUHUTD	11.43	1.321	7.239	2.870
OUHDTD	11.43	1.321	9.271	0.838
OUPNTN	11.43	1.651	6.350	3.429
OUPUTN	11.43	1.651	8.407	1.372
OUHUTU	11.43	1.981	7.239	2.210
OUPUTU	11.43	1.981	8.407	1.041
OUHDTU	11.43	1.981	9.271	0.178

Table 1: The insert names and their attendant geometries are given above. The naming convention is to list the relative size of the (O)utlet and (P)ost radii and the film (T)hickness as either (D)own or (U)p from (N)ominal. In some inserts the (H)eight of the step plus film thickness is referenced instead of the gas post radius.

Gas and liquid flow rates are controlled using calibrated sonic nozzles and cavitating venturis, respectively. The calibration and selected pressure transducers allow mass flow rates to be known to within 0.227 g/s (+\-0.0005 lb/s), ~0.25%. A valve downstream of the venturi (but upstream of the injector) insured that there was sufficient back pressure to minimize acoustic noise. All tests are performed with atmospheric back pressure. The gas flow rates were varied from 0.0187-0.0798 kg/s (0.0413-0.1760 lb/s) with clusters around 0.05, 0.075, 0.1 and 0.15 lb/s. The liquid flow rates were varied from 0.0236-0.0794 kg/s (0.0520-0.1750 lb/s) with similar clustering. The momentum flux ratio, defined using the mass flow rates along with flow areas based on the initial film thickness for the liquid and the average gas post height—$(r_p+r_o)/2 = r_p+(s+\tau)/2$, varied from around 10 to around 1100.

A dpss laser was split and expanded into two sheets. These sheets were oriented 180° from one another along the centerline of the injector or spray. Using this lighting, high speed images were taken of the film inside the injector cup (the acrylic section). A Vision Research Phantom v7.3 camera positioned 90° from the sheets was used to capture the video at 6006 fps. The exposure time was 150 microseconds. For a selection of test conditions the laser sheet was moved downstream of the injector cup so that about 63 mm of the spray was recorded. The video of the spray was captured at 3000 fps with an exposure time of 310 microseconds. The laser provided insufficient lighting to achieve the 6006 fps rate. The general laser set-up is shown in Fig. 2.

The injector cup video was processed using a custom Matlab routine in order to extract the film profile. More information on this image-processing routine may be found in a prior paper[5]. The video results of the spray are included in qualitative form only. Consequently, the only processing was changes in brightness and contrast to enhance their viewability.

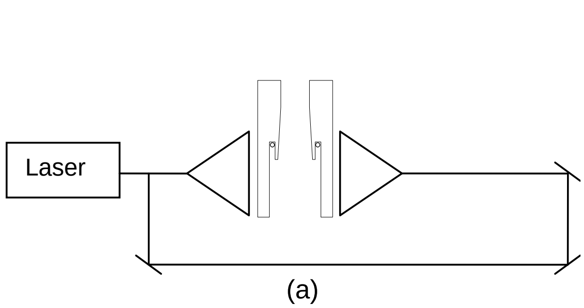

Figure 2: The laser set-up involved producing laser sheets (shown as triangles above) using cylindrical lenses. The sheet was used to illuminate the injector cup (a) or the spray just downstream of the cup (b).

RESULTS

The swirling liquid spray adds complexity to the flow inside the injector. The flow is made even more complex because the injector and film geometry often cause separated gas flow and recirculation zones, particularly near the lip of the plate initially separating the gas and liquid. The swirling liquid flow can lead to departures from axisymmetry. A feedback loop may be developed between these departures and the gas flow as gas-flow over disturbances on the surface of the liquid will cause the disturbances to distort and break up into droplets. Further complicating this flow is the competition between the momentum vectors of the gas and liquid. The liquid initially has a large tangential component while the gas has no tangential component. So, while swirling flow in the film and even in some of the two-phase droplet-gas mixture is seen at low momentum flux ratios, at high momentum flux ratios the downstream mixture of droplets and gas has lost most or all of its swirl. The swirl and attendant asymmetries, the coupling between these asymmetries, the gas flow and the droplet production and the competition between the gas and liquid flow directions may all contribute to the spray nonuniformities discussed below.

Video and by-eye observations show evidence of five types of nonuniformities. Three involve changes of the spray centerline—leaning, bouncing and oscillating—and two involve changes in the mass exiting the injectors—axisymmetric and asymmetric pulsing. Leaning, shown in Fig. 3, is the stable or nearly stable offset of the spray's centerline: instead of the centerline being aligned with that of the injector, it is tilted at a different angle. The centerline departure occurs immediately downstream of the injector. Bouncing and oscillating also refer to centerline departures in the spray. In bouncing the spray tends to prefer a particular direction but bounces between that preference and another orientation. Two frames of the video several seconds apart illustrate this behavior (Fig. 4). Oscillating is characterized by repeated, rapid departures about the injector centerline. The variations during oscillating are higher frequency and less random than in bouncing, but there is no hard line between the two behaviors. Also, the departures from the centerline are less severe in oscillating versus bouncing sprays. Oscillating behavior is shown in Fig. 5. Pulsing, as its name suggests, involves pulses of additional mass exiting the injector. There are two types of pulsing—axisymmetric, where an axisymmetric (or nearly so) disturbance forms and is shed, and asymmetric, where mass is shed from a localized area of the injector. Figure 6 shows axisymmetric pulsing while Fig. 7

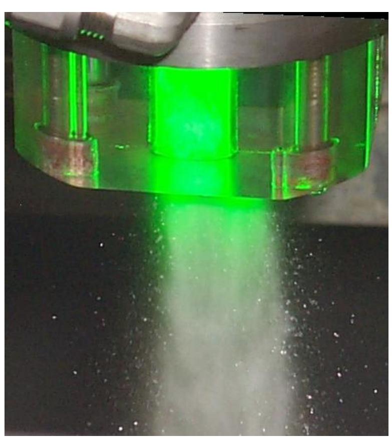

Figure 3: Leaning exists when the spray centerline differs from the injector centerline. This photograph is annotated with the centerline of the injector (dash-dot line) and the spray (dashed line).

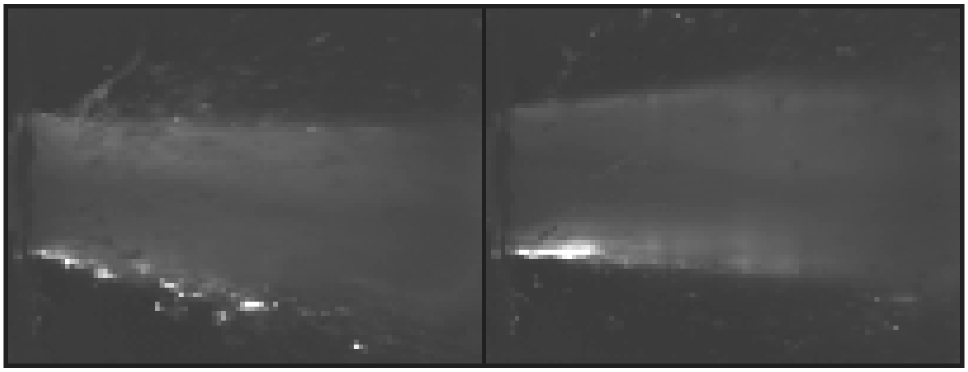

Figure 4: Two frames of video (~81.5 ms apart) show the two typical states for a bouncing spray.

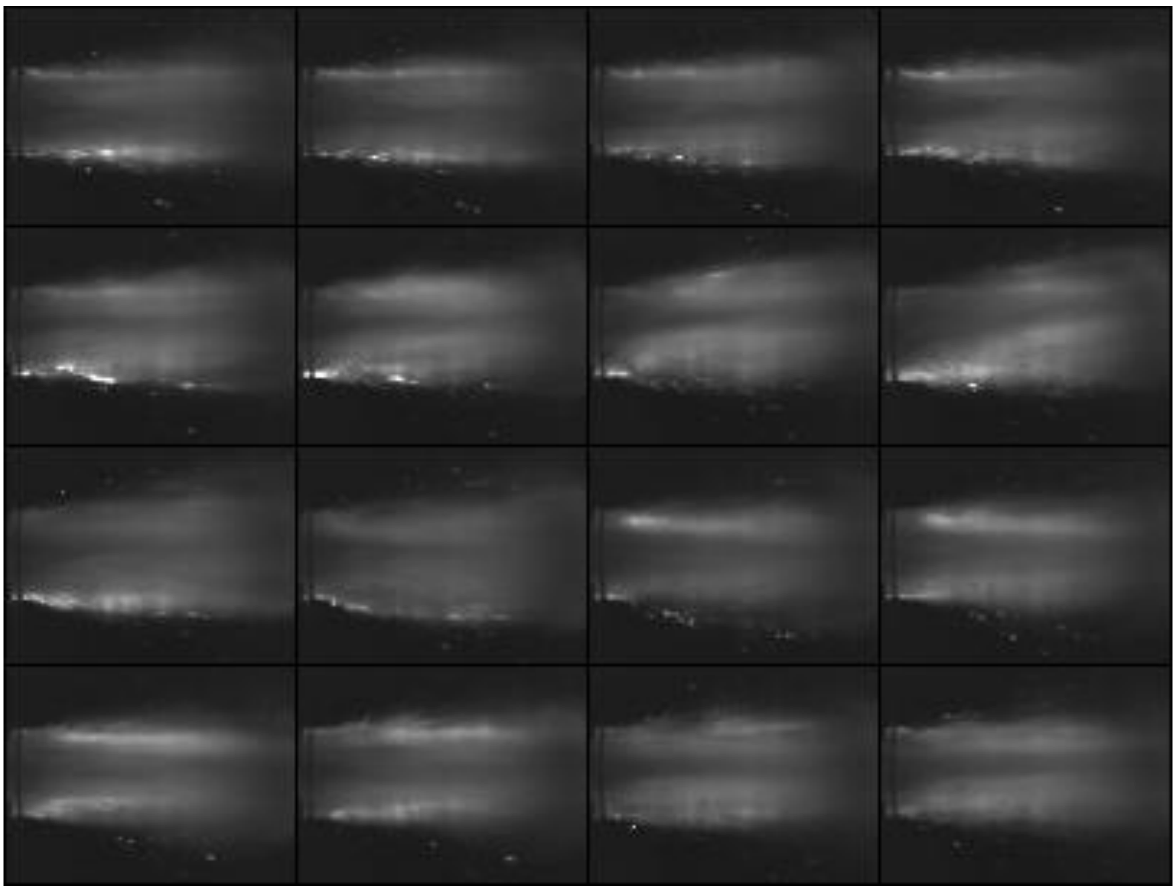

Figure 5: This time montage (read left-to-right then top-to-bottom) of a spray shows some of the changes seen during oscillation; images are taken 0.33 ms apart. Careful attention to the dark “core” in the middle of the spray images helps to show the oscillation. These changes are much more visible in moving images.

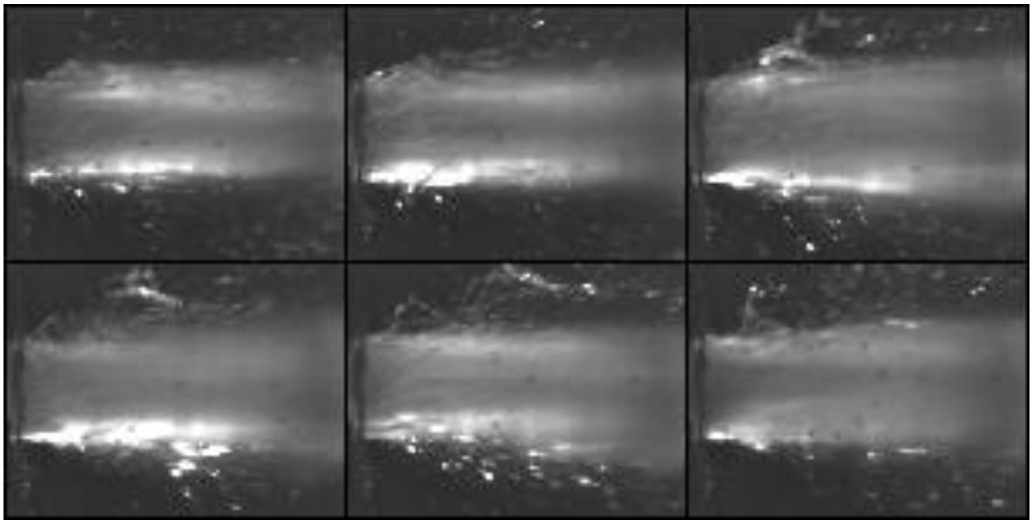

Figure 6: Pictures every 1.67 ms show the spray behavior during axisymmetric pulsing. The unevenness in lighting between the top and bottom in the images is a result of uneven beam splitting, not the result of a denser spray on the bottom of the image.

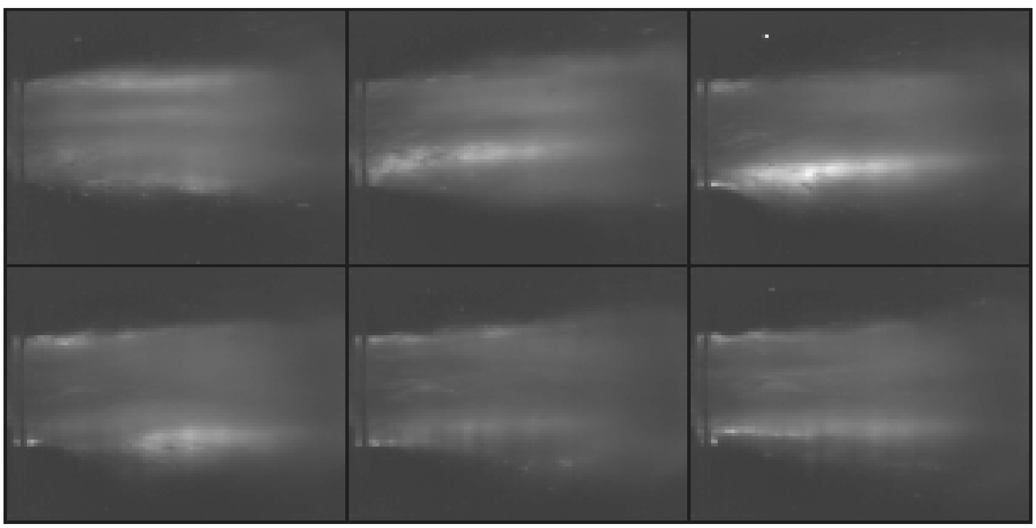

Figure 7: Asymmetric pulsing is shown through a series of pictures 0.33 ms apart. The bright streak which occurs near the bottom of the spray is a sudden increase in opacity in the spray indicating a pulse of mass.

shows asymmetric pulsing. Axisymmetric pulsing is often accompanied by a “popping” sound not unlike, in tone and duration, that of a single kernel of popcorn popping. This type of pulsing may also be accompanied by changes in spray angle (a sudden increase); otherwise, it is accompanied by a more opaque looking spray due to changes in droplet number or size within the cone. Because asymmetric pulsing is localized, its appearance is different with “streaks” of higher opacity or spurts of large droplets observed on the outer edge of the spray. While the occurance and magnitude of these behaviors depend on the injector geometry and operating conditions, the general events and driving forces leading to them is believed to remain similar across the different geometries and conditions.

The leaning behavior is one of the easiest to observe with the naked eye because the departures are often dramatic and human eyes are good at observing angular deviations. Also, leaning, as defined,

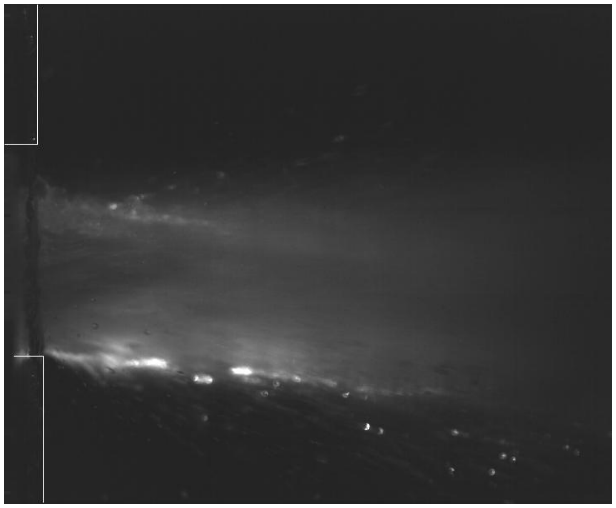

Figure 8: Leaning sprays are not attached to the injector wall at the exit of the injector (shown by lines).

occurs over an extended period of time. Initially, this behavior was suspected to be the result of machining imperfections. To test this hypothesis, the injector cup was rotated 90, 180 and 270° from its nominal position. Regardless of orientation, the spray continues to lean in the same direction as measured from laboratory coordinates. If leaning was related to imperfection in the injector, the direction would be expected to remain constant in the injector coordinates instead. Another possible cause of leaning, supply line biasing, was also ruled out. Several feet of fixed supply lines are followed by about 3 feet of flex line immediately prior to the test article. The orientation and bend of the flex line was altered over a wide range and no change in leaning behavior was observed. It appears then, that leaning is the result of in-cup interaction between the liquid and gas. Further support for this conclusion is the reproducibility of the leaning—at given operating conditions and geometry a spray will always lean in the same direction regardless of how the operating condition was approach and even after the injector has been dis- and re-assembled. (Note, however, that at different flow conditions the spray may reproducibly lean in the opposite direction. See, for example, Table 3 for how operating conditions may change leaning behavior.)

When leaning occurs, the gas flow appears to be unattached from the outlet edge of the injector cup on one side of the injector. This separation can be seen on in-cup videos as well as in the spray videos (Figs. 8 & 9). No obvious and consistent upstream liquid differences were noted between leaning and nonleaning sprays with similar geometry or operating conditions. Furthermore, in bouncing sprays (where leaning periodically occurs) the separation point of the gas appears to move upstream and then stabilize with no obvious changes in the liquid film behavior. Because the flow is swirling and the visualization is taken from a centerline slice, driving film abnormalities could be out of the viewing area; however, the swirling flow would be expected to carry any abnormality around the cup moving it in and

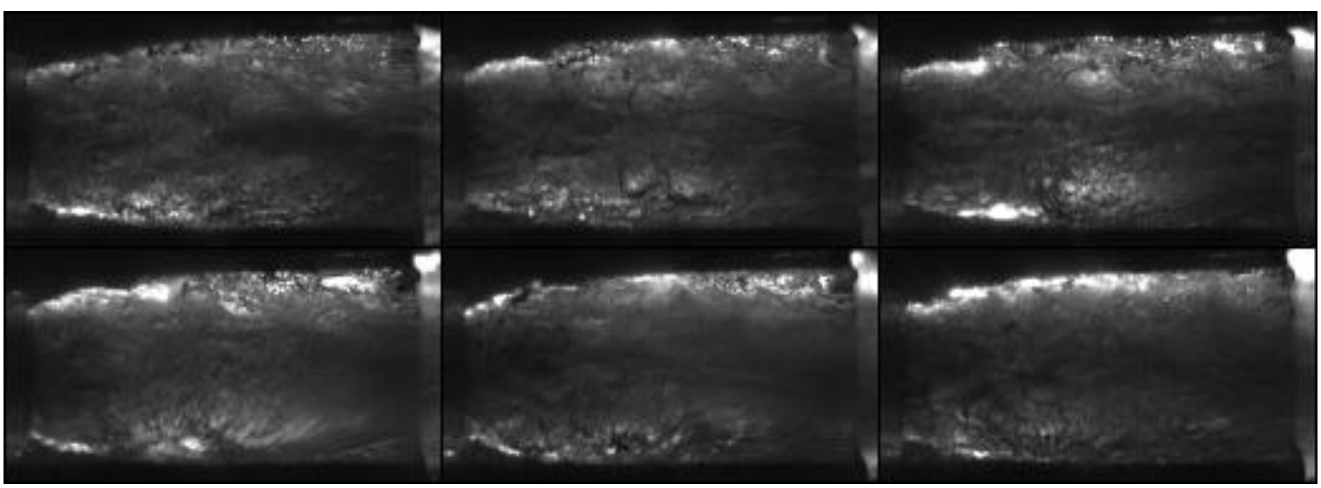

Figure 9: While difficult to see in this still, small format, the in-cup video frames show backflow—lighter areas at the top right of the photographs—during a bouncing event where the spray leans to the right in the laboratory framework (up in the framework of the above photographs). Time runs right-to-left then top-to-bottom with 1.67 ms between frames. The geometry shown is ONPNTN operating with 529 as the momentum flux ratio.

out of the field of view and preventing any stabilization of the offset centerline. Experiments, discussed later and presented in Table 3, indicate that leaning occurs at specific momentum flux ratios not necessarily specific gas flow rates. In other words, it must be caused by a combination of gas and liquid behavior. At the present time, however, the exact mechanism(s) involved remain unknown. Another unknown parameter which may affect this behavior is the length of the injector body or, at least, its length with respect to the maximum film height or length. The currently tested injector body is longer than would normally be used in a rocket engine in order to better visualize the film over a wide array of conditions. Future plans include tests with different lengths of the injector cup.

Bouncing is strongly related to the leaning behavior as it is essentially the movement from one leaning state to center or another leaning state. Oscillating is also related to leaning as it is a rapid movement about the injector centerline. However, this can be somewhat more difficult to observe as the variation can be very rapid and between only slightly off-set conditions. The resulting spray sometimes appears to have a larger cone angle and only on close inspection is it apparent that the cone angle is not increased but the spray centerline is rapidly changing. As with leaning, testing has been completed to ensure that bouncing and oscillating do not change appreciably with injector orientation or feed line orientation. Consistency in these behaviors is less easily ascertained than that of leaning, but it can be reported that the spray does not cease the unsteady behavior or alter it appreciably with these changes. Again, the exact cause(s) is unknown, but likely relate to unsteadiness in the driving forces which generate leaning. Figure 9 shows the in-cup evolution of a bounce. The lighter area (circled) indicates the separated gas flow which contains fewer droplets than the main flow because it is coming from outside the injector body away from the spray centerline. What causes this separation bubble to form or collapse/escape is, as discussed out earlier, yet unknown. The leaning itself is a result of the separation bubble displacing the main droplet-laden gas flow. When the bubble collapses or is pushed downstream, the centerline of the main gas flow rebounds and briefly forms a sort of sinuous shape within the injector. In all conditions where this behavior was examined the main flow restabilizes and recenters prior to the formation of another separation bubble. In other words, the rebound from the removal of the separated flow condition does not appear to be an initiator for a subsequent cycle of separated flow.

Similar separated flow was not observed in videos of oscillating sprays. However, this failure could be due to the rapidity of the behavior or the smaller size of separation bubbles which would produce the small oscillating departures. On the other hand, when oscillation occurs in long films (that is, at low momentum flux ratios) a multitude of fast-moving waves often appear on the surface of the film. These waves are not unlike those observed in pulsing (Figs. 10 & 11), but generally move more rapidly and tend to be asymmetric. At high momentum flux ratios, the film is very short and wave behavior either does not occur or is difficult to observe. Short oscillating sprays do, on occasion, exhibit short, rapid changes in film length. Pending further investigation, it appears that while oscillation may occur as an extreme case of bouncing and have similar driving forces, it may also occur through other mechanisms more strongly related to visible surface disturbances.

Pulsing can be the most difficult behavior to observe with the naked eye. The main reason for this difficulty is the transience of the behavior. A pulse of liquid travels through the spray at speeds approaching that of the gas flow—often 100's of feet per second. Unless the pulsing is regular or very frequent, it can be missed. Further work in spray imaging is planned to ensure the envelopes for these behaviors are well mapped. Axisymmetric pulsing is mostly easily observed when it is accompanied by a popping sound; while pulsing occurs without popping, popping was always accompanied with pulsing. Mass flow rates are controlled by upstream pressure and a cavitating venture. The pressure drop over this venture is maintained at about 80% by a downstream valve to ensure that there are minimal variations in supply rate. Given this controlled inlet of mass and the fact that pulsing does not appear at all conditions (or even the same conditions with different geometries), this behavior is also the result of gas-liquid interaction.

When pulsing occurs, there is a localized increase in film thickness observed prior to the behavior (see Fig. 10 & 11). With axisymmetric pulsing the increase appears circumferentially being nearly or completely axisymmetric. Small departures from axisymmetry sometime occur, likely as a result of the swirling liquid velocity. In asymmetric pulsing, the increase in thickness is localized and only evident on

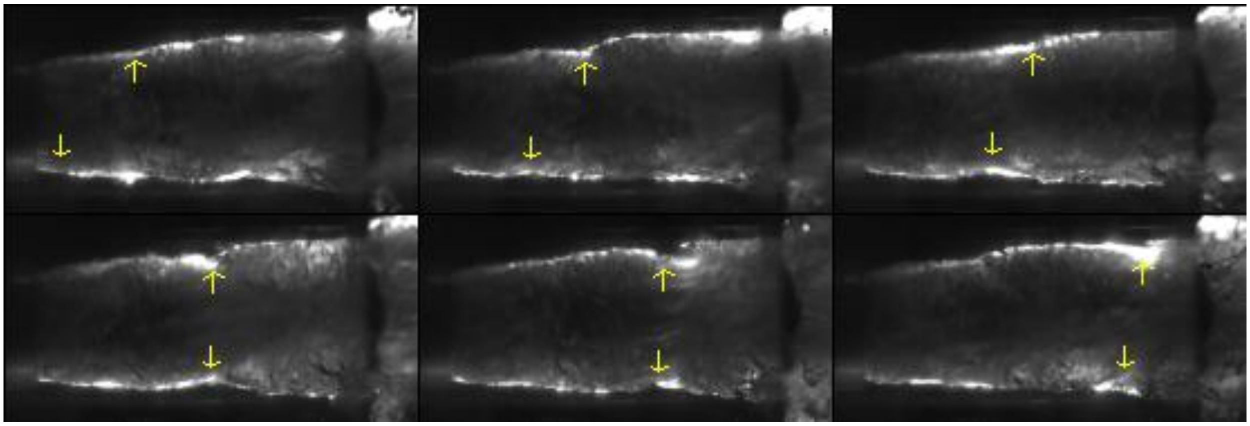

Figure 10: In-cup video frames show axisymmetric pulsing. Time runs right-to-left then top-to-bottom. The time between frames is 0.83 ms. The geometry shown is ONPNTU operating at a momentum flux ratio of 255. Arrows show the approximate center of the waves to aid in their visibility.

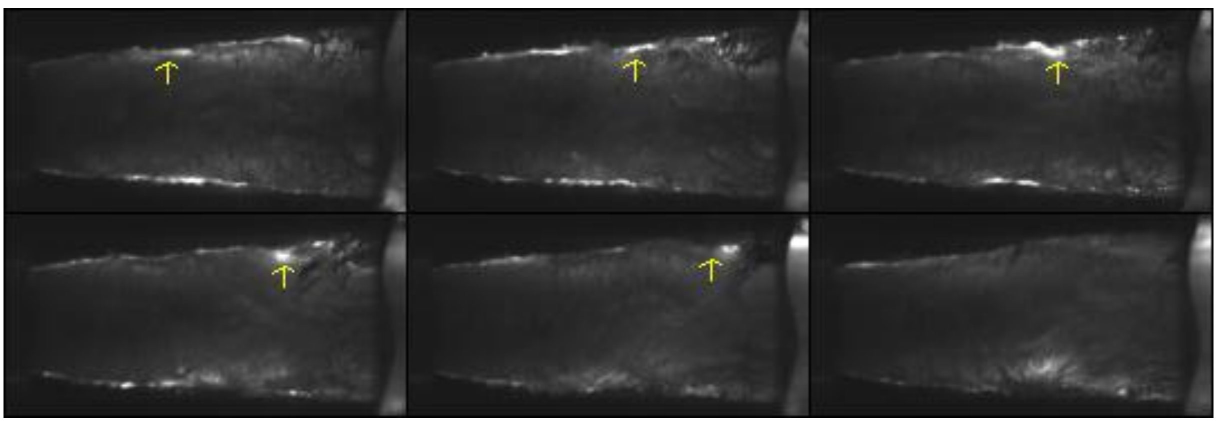

Figure 11: In-cup video frames show asymmetric pulsing. Time runs right-to-left then top-to-bottom. The time between frames is 0.67 ms. The geometry shown is ONPDTD operating at a momentum flux ratio of 89. Arrows show the approximate center of the waves to aid in their visibility.

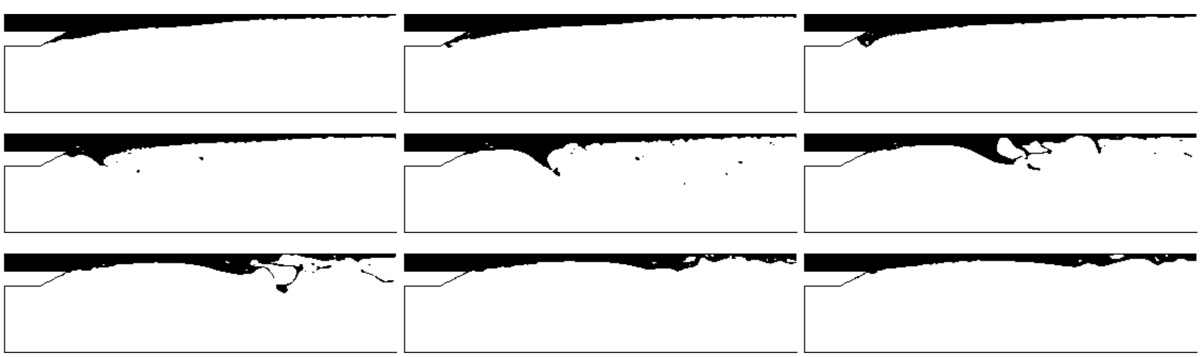

Figure 12. Axisymmetric simulation of the injector with a gas flow rate of 0.014 kg/s and an axial liquid velocity of 0.347 m/s. [6] The black region represents the liquid. The flow is fully developed and images are given at 1.5 ms intervals from left to right, top to bottom.

one side of the visualized film. These localized increases, or waves, form rapidly and are then shed downstream. It is believed that the bumps are caused by the interaction of the liquid and gas at the end of the separating lip. In some situations, the recirculating gas flow pulls a small amount of liquid up over the lip. This configuration is unsteady, however, and causes a disruption in the recirculating flow. At this point any above lip liquid, as well as some of the liquid just downstream of the lip, are pushed downstream creating a bump. Obviously, knife-edged or small thickness lips are more prone to this behavior than thicker lips. However, thick lips can also generate pulsing behavior at the lip. The liquid fills in along the lip creating a smooth transition for the gas, but a thicker lip requires more liquid and the liquid is more distant from the main flow, so may be more easily displaced in large amounts. Similar behavior has been observed in prior CFD results (Fig. 12)[6]. The in-cup visualizations do not seem to capture the initial bump formation, but do capture the shedding of the bump. It should be mentioned that while the qualitative behavior of the CFD and experiments agree, as shown in Fig. 12, this concordance is not achieved at the same operating conditions. This lack of quantitative agreement and the inability to observe bump formation dynamics, leaves some doubt as to the exact creation mechanism. It is possible that bumps are formed through other unsteadiness in the recirculating gas flow and, as such, actually form somewhat downstream of the lip. Future work with a flat geometry (allowing better flow visualization) should shed more light onto this phenomenon.

All of these behaviors—leaning, bouncing, oscillating and pulsing—are undesirable and the designer would like to eliminate or minimize them in a rocket injector. As evidenced above, both the operating conditions and the injector geometry play important roles in determining whether spray variations occur. While the injector designer must meet a specific mixture ratio in a rocket engine, the operating conditions of a GCSC can still be considered in the design space through the use of few, larger or many, smaller elements. In addition to operating conditions, which may have a limited range of alterability, there is a wide array of changes which may be made to the internal geometry of the injector in order to achieve spray uniformity. The impact of geometry (and operating condition) changes on atomization performance is addressed in a prior work[5]. Here, then, some design guidance is attempted for aiding the engineer in achieve the desired spray uniformity.

Again, a range of operating conditions with mass flow rates of 0.0187-0.0798 kg/s for the gas and 0.0236-0.0794 kg/s for the liquid were tested. These ranges correspond to range of momentum flux ratios from about 10-1100. A sweep of this momentum flux range was made with each injector geometry tested. Again, the specifics of the geometries may be found in Table 1. Observation of nonuniform behavior suggest that the higher the momentum flux ratio, the more stable the spray will be; this uniformity is reflected somewhat in the stability of the film length—high momentum flux operating conditions tend to produce sprays with lower standard deviation in film length[5]. Several inserts, particularly those with 7.620 mm outlet radius, exhibited nonuniformites at low momentum flux ratios but becomes uniform at higher ratios. Additionally, high momentum flux ratio operations are more subject to oscillation than the other nonuniformities. If the oscillation frequency is well away from any chamber frequencies or resonances and the departures from centerline are small, engines can probably tolerate this behavior. Also, as discussed in the pulsing discussion, small steps (such as knife edges) are particularly unstable. Pulsing may occur due to liquid being moved up the step, but sharp edges at the phase contact also create high levels of vorticity[7] which are likely detrimental to stable, uniform sprays. Very large steps may also cause issues due to strong gas-phase separation and the potential to choke the flow prior to liquid-gas contact. The largest lips tested here were prone to bouncing and pulsing when the outlet diameter was large, but exhibited very uniform behavior when the outlet diameter was small. In general, smaller outlet diameters were more uniform than the larger outlets, so the size of the gas core appears to effect stability. Due to this effect, an exact envelope of step heights cannot be given, but will depend on outlet diameter.

A subexperiment was briefly undertaken to examine the effect of operating conditions on the stability of the spray with insert/geometry ONPNTN. While the liquid flow rate was held fixed at 0.0336 kg/s, the gas flow rate was slowly increased from 0.0122 to 0.0717 kg/s. As the gas velocity was increased, the spray moved from a two-cone, stable, centered spray to a spray which bounced and preferred to lean left. A bit of an additional increase in gas velocity and the flow stabilized to leaning left. Further increases caused bouncing again, with additional increases leading to a preference for the right.

Eventually, the spray leaned steadily right. At the upper range of gas flows, the spray bounced at a high frequency but showed no preference for right or left, bouncing equally about the center. A table indicated the operating conditions for the various behaviors is given as Table 3. The second half of Table 3 presents the other half of this subexperiement—the gas flow rate was fixed at 0.0363 kg/s and the liquid flow rate was slowly increased from 0.0268 to 0.0513 kg/s. A similar shift in behavior was seen with the increase in liquid flow rate (although it is reversed since the momentum flux ratio is now decreasing instead of increasing). Again, these results suggest that even if the injector design generates a nonuniform spray, operating at high momentum flux ratios at least generates a spray with no directional bias. However, once the injector geometry is set, the designer has less ability to alter the operating conditions as any changes with fixed geometry will affect the mixture ratio of the engine, so careful prior planning is needed.

Gas mass flow (kg/s)	Liquid mass flow (kg/s)	Approx. Momentum flux ratio	Behavior
0.0122	0.0336	24	Start point; little center spray but seems uniform
0.0272	0.0336	117	starts bouncing to left, eventually leans left
0.0322	0.0336	164	starts to bounce right, eventually leans right
0.0445	0.0336	313	bounces fully left-to-right
0.0499	0.0336	395	oscillates
0.0717	0.0336	814	Stopping point, still experiencing oscillations
0.0363	0.0268	328	Start point; oscillating
0.0363	0.0272	317	begins bouncing right, eventually leans right
0.0363	0.0363	179	starts bouncing left, eventually leans left
0.0363	0.0467	108	bounces to left but mostly centered
0.0363	0.0513	90	Stopping point

Table 2: The gas mass flow rate was varied with the liquid flow rate was held constant, and vice versa. The uniformity behavior of the spray was observed and is reported here. Due to the manner of experiment, the accuracy of the reported flow rates is less than the main experiment: uncertainties are perhaps as much as 0.005 kg/s.

CONCLUSIONS

Tested of a gas-centered swirl-coaxial injector found several nonuniformites can appear in the sprays. These nonuniformities may be grouped as effecting the spray centerline—leaning, bouncing and oscillating—or effecting the temporal distribution of mass—axisymmetric and asymmetric pulsing. Both groups of nonuniformities are due to interactions between the gas and the liquid; several obvious root causes such as machining errors and inlet biases have been ruled out. The behaviors are repeatable for a given geometry and operating condition. Reproducible centerline disruptions are found at similar momentum flux ratios both by holding the gas constant while varying the liquid flow rate and by holding the liquid constant while varying the gas flow rate. The root cause of the nonuniformities remain under investigation. However, bouncing and leaning appear to be related to gas-phase recirculation at the end of the injector cup which is localized to one area near the outlet. Leaning occurs when this separated gas flow is stable and bouncing occurs when it is occasionally shed. Oscillating may also be related to this gas-phase anomaly, but visual evidence does not show obvious recirculation as in bouncing and leaning. In some cases, oscillation may, instead, be due to the unsteady flow of gas over moving waves on the film surface. Pulsing is caused by the formation and shedding of localized or axisymmetric “bumps” of liquid as observed in in-cup visualizations. The initiation mechanism of the bump has not been verified but is believed to be related to flow near the separating lip.

The lip geometry, gas-post radius and operating momentum flux ratio are important parameters for developing injectors with minimal or no nonuniformities. The higher the momentum flux ratio (a range of ~10-1100 was tested) the more uniform the spray tends to be. Some injector geometries exhibit nonuniformities at low momentum flux ratios but become uniform as the ratio is increased. Nonuniformities at high momentum flux ratios tended to be oscillations rather than leaning, bouncing or pulsing. Over the small range tested, 7.62-11.43 mm, smaller outlet radii injectors were, in general, more uniform than larger radii injectors. Within reason, the design should strive for small injector elements, then, particularly as smaller elements can achieve higher momentum flux ratios at a given mixture ratio. Finally, sharp-edged separating lips were found to produce particularly unstable sprays, especially in terms of pulsing behavior. Designers should not try to minimize lip height as a way to achieve a stable, uniform spray.

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